Acoustic trapping with a high frequency linear phased array

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A high frequency ultrasonic phased array is shown to be capable of trapping and translating microparticles precisely and efficiently, made possible due to the fact that the acoustic beam produced by a phased array can be both focused and steered. Acoustic manipulation of microparticles by a phased array is advantageous over a single element transducer since there is no mechanical movement required for the array. Experimental results show that 45 μm diameter polystyrene microspheres can be easily and accurately trapped and moved to desired positions by a 64-element 26 MHz phased array. © 2012 American Institute of Physics. [http://dx.doi.org/10.1063/1.4766912]

Similar to the trapping mechanism of optical tweezers,[1,2] when acoustic gradient force (from refraction) exceeds scattering force (from reflection), an object can be attracted and trapped by a tightly focused ultrasound beam.[3,4] The direct exposure of cells to the optical trapping laser beam may induce photodamage,[5] however, it was demonstrated that the thermal and mechanical effects in acoustic trapping are negligible when the energy is maintained in the diagnostic range.[6] Recently, high frequency single element ultrasonic transducers have been used to carry out single beam acoustic trapping. In these approaches, in order to move a trapped microparticle, a mechanical scanning stage has to be utilized to move the transducer and its focus.[7–9] In this paper, we present results showing that it is possible to trap and move microparticles with a high frequency ultrasonic linear phased array without mechanical movement of the transducer.

An ultrasonic linear phased array transducer (or simply called phased array) is a transducer consisting of multiple small transducer elements, which usually are rectangular in shape and arranged on a straight line. Ultrasonic phased arrays have been widely used in biomedical imaging[10] and industrial nondestructive testing.[11] The advantages of phased array transducers over conventional single element transducers are their capabilities of steering the ultrasound beam into different directions and/or changing the focus at different depths, not by mechanically moving transducers but by applying electronic phase shift/time delays on the transmitting pulses to the elements of the phased array. Eliminating the mechanical movement of the transducer increases the system reliability and the speed of the experiment.

A customized lead zirconate titanate (PZT-5 H) 2-2 composite linear phased array transducer was fabricated with traditional array technology.[12] The center frequency of the phased array is 26.3 MHz. The array has 64 small elements arranged on a straight line in the azimuthal direction. The elevation length and lateral width of one element are 2 mm and 24 μm, respectively. The kerf between two adjacent elements is 6 μm. The F-number of the phased array is 2.6.

A field programmable gate array (FPGA) based 64-channel transmit beamformer and a 64-channel pulser were also developed to drive the phased array. The transmit beamformer could send out 128 (64 pairs) delayed trigger signals,[13] with which the pulser could generate 64 bipolar pulses of 50 V peak-to-peak voltage to excite the 64-element phased array. The different transmit time delay patterns could be loaded into the transmit beamformer to steer and focus the ultrasound beam.

From phased array geometry (Fig. 1), the transmit time delay of any element of a phased array for a specific focal point can be calculated from the equation below[14]

$$\tau_i = \left[\sqrt{(x_i - x_{fp})^2 + z_{fp}^2} - r_{fp} \right] \bigg/ c,$$

which allows the ultrasound wave from all elements to arrive at the transmit focal point at the same time. In the equation above, τ_i is the transmit time delay for array element i, and x_i is the distance from the center of array element i to the origin. The symbols x_{fp} and z_{fp} are the coordinates of the focal point while r_{fp} is the distance from the origin to the focal point, and c is the sound speed in the medium surrounding the array.

In the experiment, three parabolic transmit time delay patterns (Fig. 2) were loaded into the FPGA based transmit beamformer, which would focus the propagating ultrasound waves to three specific points. Time delay pattern #1 generated a focus at 5 mm (axial direction) and 0 μm (lateral direction) away from the center of the phased array. Time delay pattern #2 and #3 generated two foci at the same axial distance (5 mm) as the delay pattern #1, but at 350 μm and 450 μm (lateral direction) away from the center of the phased array, respectively.

Using Field II ultrasound simulation,[15,16] the normalized ultrasound intensity (in dB) is plotted in Fig. 3, which

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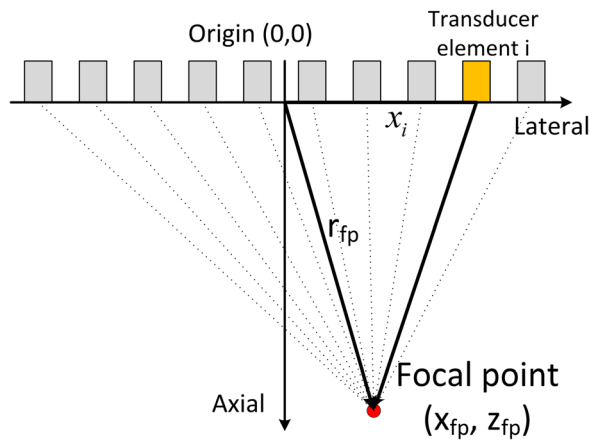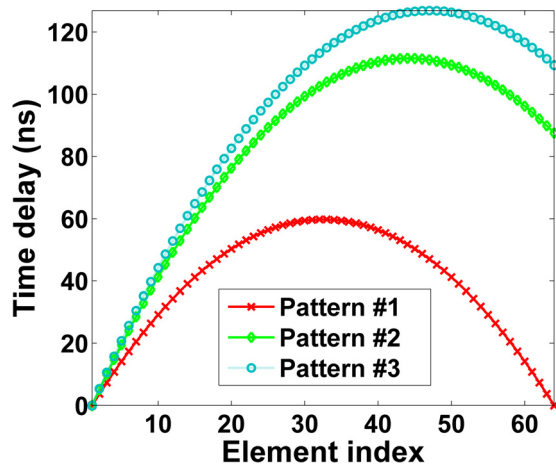
FIG. 1. Phased array geometry and focal point.

FIG. 2. Three transmit time delay patterns were loaded into the transmit beamformer before the experiment.
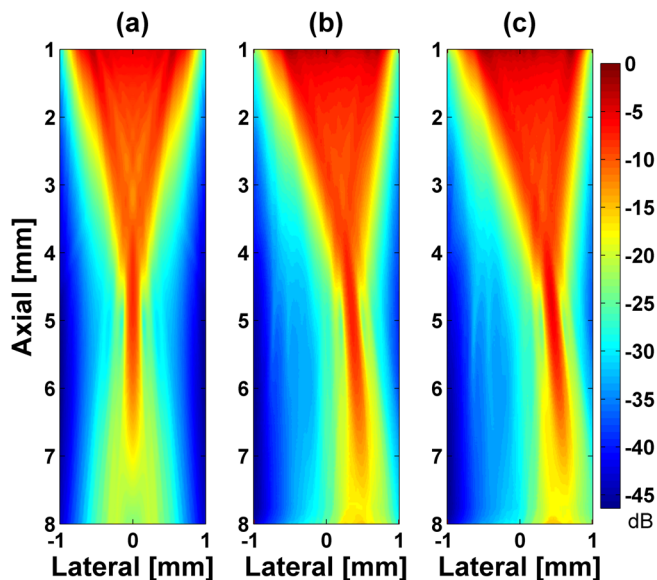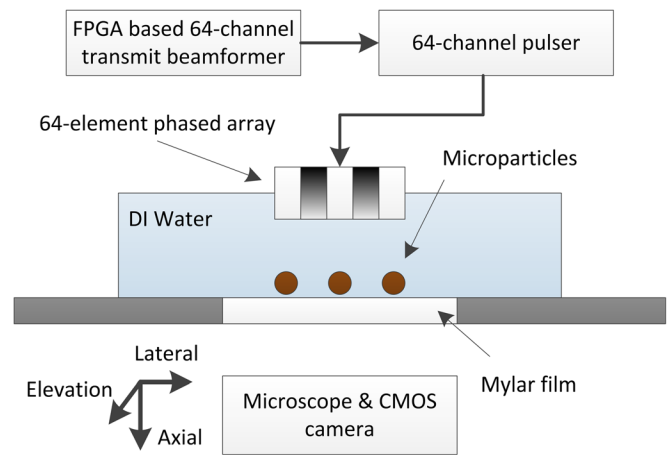

FIG. 3. Simulation of the ultrasound intensity when the phased array steers the beam and focuses at three different lateral positions where axial positions are all 5 mm. The color represents the normalized intensity. (a) $0\,\mu$m in lateral direction. (b) $350\,\mu$m in lateral direction. (c) $450\,\mu$m in lateral direction.

FIG. 4. Block diagram of the linear phased array acoustic trapping and moving experiment.

demonstrates by implementing three transmit time delay patterns, the phased array can steer the beam and focus at $0\,\mu$m, $350\,\mu$m, and $450\,\mu$m away from the center of the phased array in the lateral direction, respectively. The highly focused ultrasound could generate a sharp intensity variation in the lateral direction and allow particles to be trapped at desired positions.

The experimental arrangement for acoustic trapping and translation of microparticles with a phased array is shown in Fig. 4. The high frequency phased array was mounted on a transducer holder. The array and the holder remained motionless during the experiment. The phased array was immersed in deionized (DI) water in a designed chamber. There was a transparent mylar film on the bottom of the chamber. The motion of the microparticles could be observed through the mylar film by an inverted microscope and recorded by a camera attached to the microscope. Polystyrene microspheres of $45\,\mu$m mean diameter were added into the chamber as targeted particles to be trapped and moved.

In the experiment, the position of the phased array was fixed. As the experiment began, the micro-particles were at rest, shown in Fig. 5(a). After applying transmit time delay pattern #1 and exciting the phased array elements, the ultrasound beam was transmitted and focused at $0\,\mu$m in the lateral direction, and the micro-particles were being trapped, shown in Fig. 5(b). Next, in Fig. 5(c), applying delay pattern #2, the micro-particles travelled to the position $350\,\mu$m away from the original trapping location in the lateral direction. Again, with the time delay pattern #3, the micro-particles were further moved to the position $450\,\mu$m away from the original trapping location, shown in Fig. 5(d). To move the particles back to the original trapping location, we then applied delay pattern #2 to move the particles back to the "$350\,\mu$m" position, shown in Fig. 5(e). Continued applying delay pattern #1, the particles eventually moved back to the original trapping position, shown in Fig. 5(e).

In summary, the experimental results demonstrate that the high frequency phased array is capable of precisely trapping and moving microparticles without mechanical movement of a transducer. The lateral beam width of the current phased array was around $200\,\mu$m, it could not yet trap and
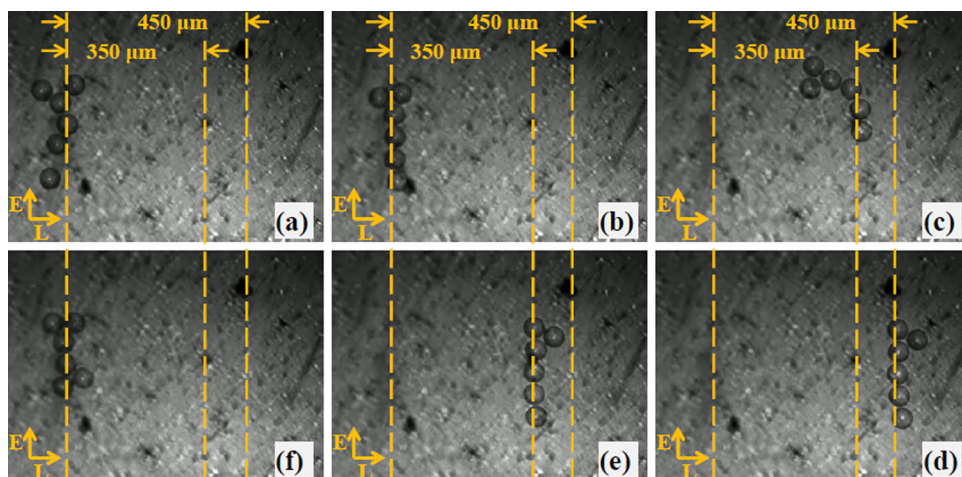
FIG. 5. Micro-particles (45 μm mean diameter) were trapped and moved with transmit different time delay patterns. E: Elevation direction; L: Lateral direction. (a) No ultrasound was transmitted. (b) Time delay pattern #1. (c) Time delay pattern #2 (d) Time delay pattern #3. (e) Back to time delay pattern #2. (f) Back to time delay pattern #1 (enhanced online) [URL: http://dx.doi.org/10.1063/1.4766912.1].

move a single particle of several-micrometer diameter. Work is underway to develop a phased array with higher frequency and more elements (bigger aperture size) to form a more tightly focused beam, which should allow single particle trapping and translation. These results also suggest that microparticle trapping and translation in both lateral and elevation directions may be realized with a 2D high frequency ultrasound array.

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